AFFTC-PA-12286

Issues and Solutions to Midwave Staring FLIR Performance Measurement Over Background

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May 2012

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14. ABSTRACT
Following an in-flight squawk for poor and unstable image quality during pre-deployment operational testing at Edwards, the Edwards Benefield Anechoic Facility (BAF) electro-optics laboratory set about to duplicate what was suspected as a background temperature related sensitivity issue with the relevant family of sensors, specifically midwave staring FLIRs. The specific system in question was designed in 1992 and fielded in 1994 having relied on existing performance models available at the time which indicated the performance should have changed only slowly and tolerably as background temperature varied. However, experience at Edwards showed considerable sensor change in sensitivity related to background flux even over the seemingly small 20°C temperature variation at Edwards from late afternoon when the flights would originate and later in the evening when data acquisition was undertaken. Note that real operational environments can involve backgrounds from -40°C in northern latitudes to well over +40°C in tropical and desert areas. These were the limits used for this particular system, and in fact are still in use today due to design limitations which prevent operation above +40°C. A reasonable specification for sensors of this type to make them operationally suitable would be from -40°C to +100°C to accommodate hot environments populated with operating vehicles. Note also that such backgrounds can even occur within a few frames of video as sensors observe a cold sky and then a hot desert. Multiple scenarios can stress sensors between these limits. Issues related to duplicating and quantifying sensor performance under these conditions were:

• No piece of commercial test equipment existed that is specifically designed to make sensitivity measurements on tactical sensors at other than room temperature. These measurements are known as noise equivalent temperature difference (NETD) and represent that temperature difference on a large resolvable target at which the sensor signal to noise ratio is 1. These measurements are repeatable and accurate at room temperature although test equipment temperature difference measurement accuracy in the ballpark of 5mK (5 thousandths of one degree centigrade or Kelvin) or less is needed and is generally provided by available equipment at room temperature. The issue is making such a measurement at low background where frosting of the target occurs.

15. SUBJECT TERMS
Background temperature related sensitivity, NETD, low background, Benefield Anechoic Facility

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May 2012

U.S. AIR FORCE

TYBRIN
THE BEST GO BEYOND

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Overview

1. Test Issues to Investigate

2. Test Methodology

3. Test Setup

4. Test Results & Issues

5. Observations

6. Path Forward

- Lack of consistent acceptable FLIR picture quality

    - "Appears as low contrast in some situations"

    - "FLIR looked pretty good when I took off and then a while later it didn't"

- **Use a lab environment to investigate the flying NETD of the most common configuration of staring midwave FLIR as a function of background**

  - Use available lab cameras as surrogates for flying system

  - Use scene projector to generate low backgrounds with programmed NETD target

  - Use FLIR RTools® software to collect digital thermographic data

  - Run scene projector with constant 5°ΔT bar over backgrounds of 20° to -40°C

  - Use blackbodies to collect data from 20°C to 100°C

  - Analyze all data to determine sensor performance dependence on quantization, fixed pattern noise, integration time and background

  - Extrapolate to other backgrounds and sensor operating modes using curve fits and established relationships

2053   2096

Background   **Target**

(UNCLASSIFIED)

4
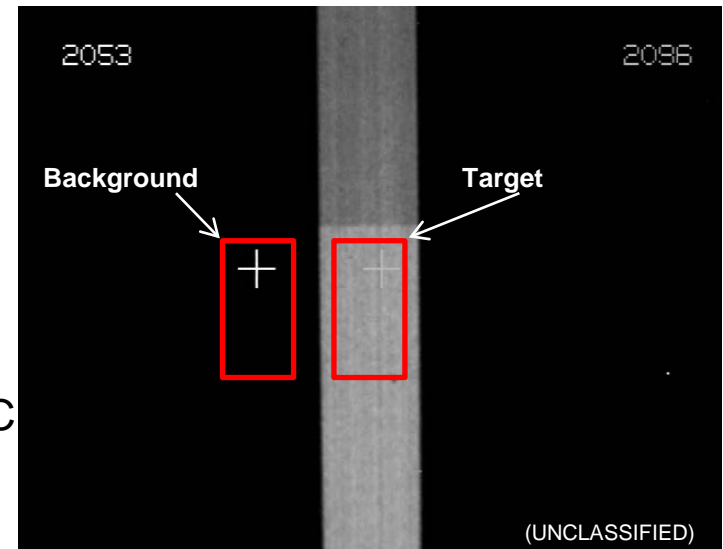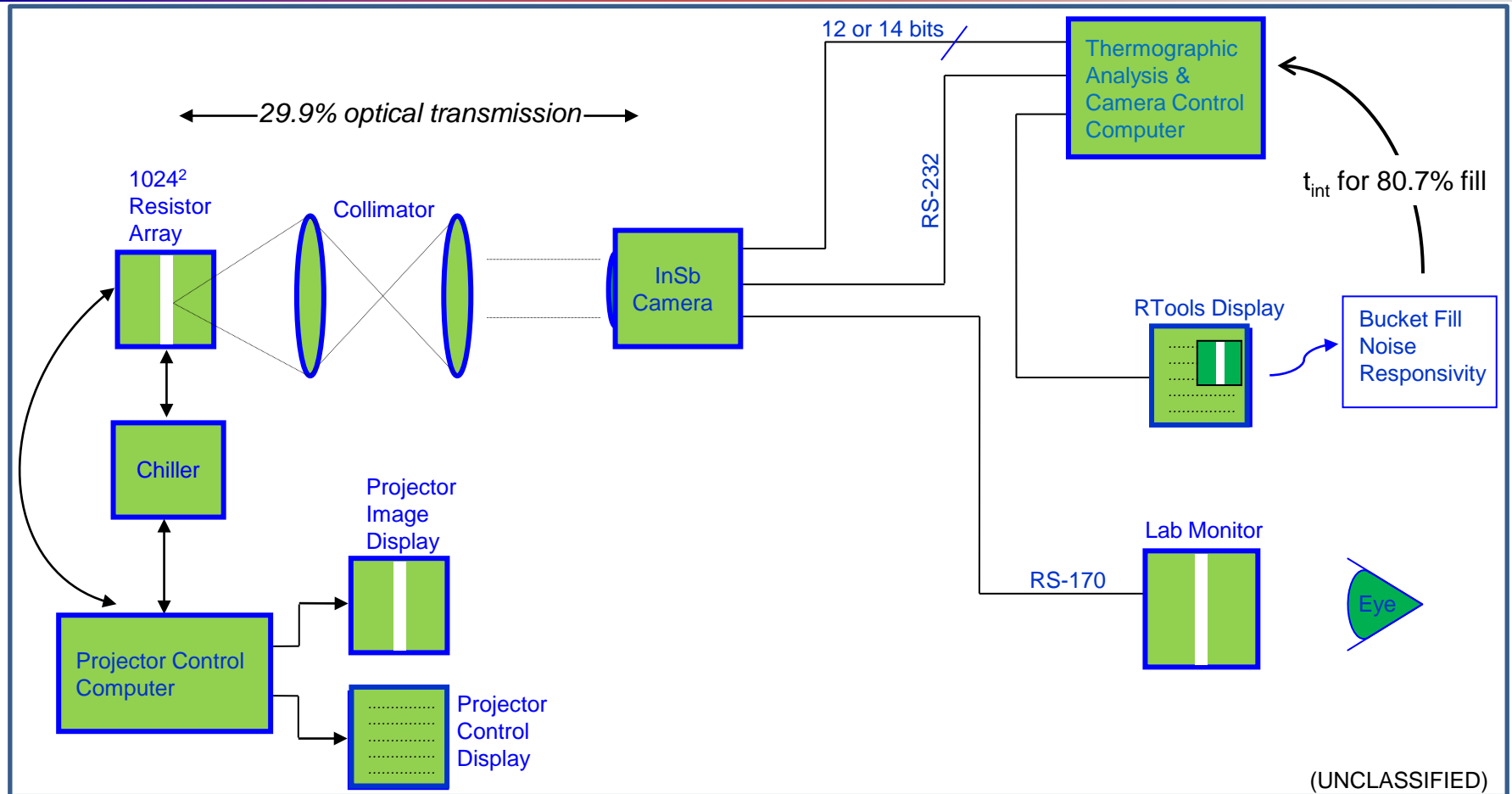
Note: Collimator has a 14.4" focal length and a 4" aperture, which will project a FOV of 7.69° using the 1024^2 resistor array

Original Data of Noise vs Bucket Fill and Background
(a)

$$y = 0.04x^2 - 4.3343x + 122.9$$
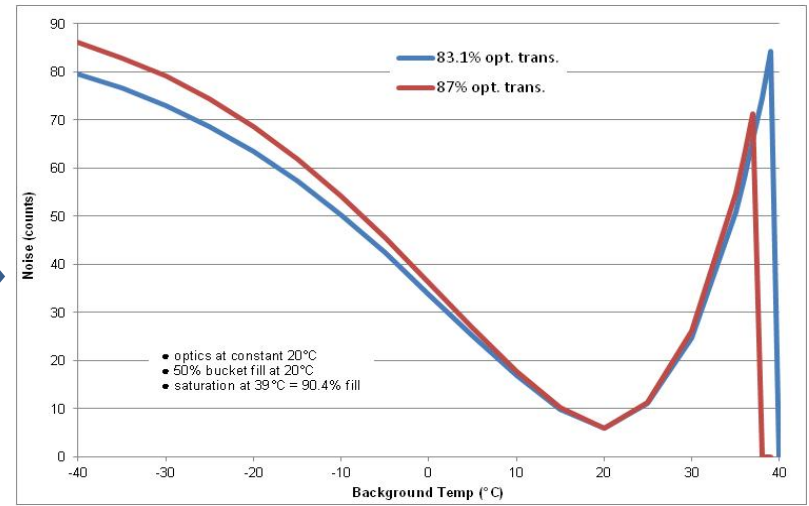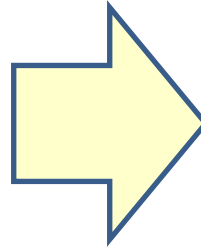
Allows Noise Extrapolation to Higher Transmissions
(b)
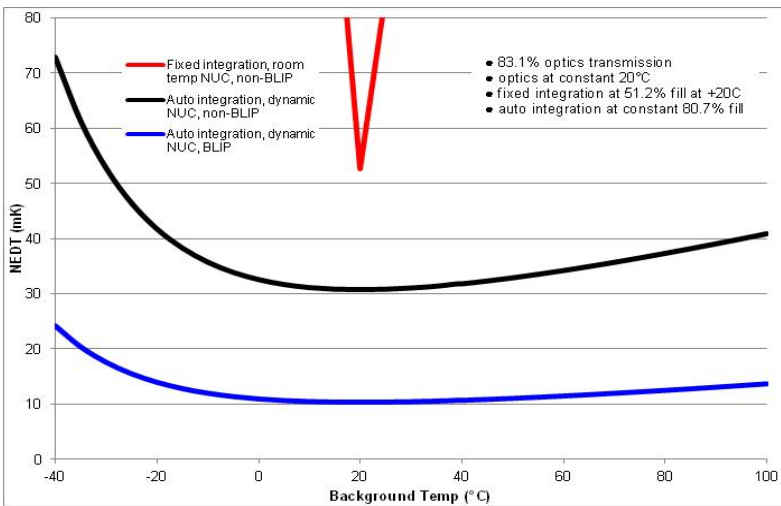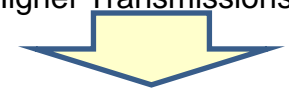
Which Allows NETD Comparison to Other Designs
(d)
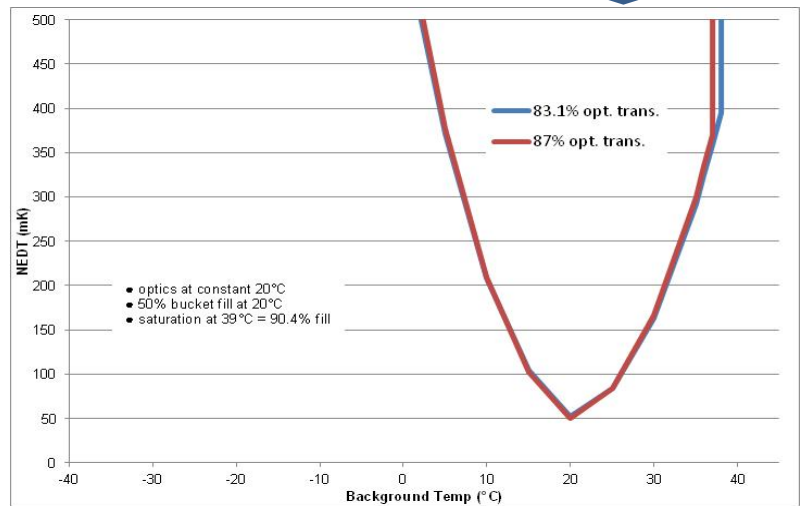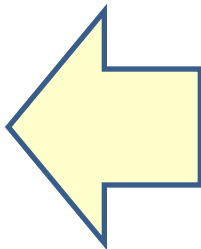
Which Predicts NETD at Higher Transmissions
(c)

7

SC6000
640x512 InSb, 25μ, f/4.1, Stirling cooler, 14 bits
variable integration and SBNUC
11/30/2011

Correct optical transmission when switching test setups at 20°C

Turbulence across hot blackbody face

Temp instability in projector

- 41.8% opt trans
- optics at room temp
- constant 80% bucket fill

Normalized Noise
Normalized Responsivity
Normalized NEDT

Relative Value

Background Temp (°C)

(a)

(b)
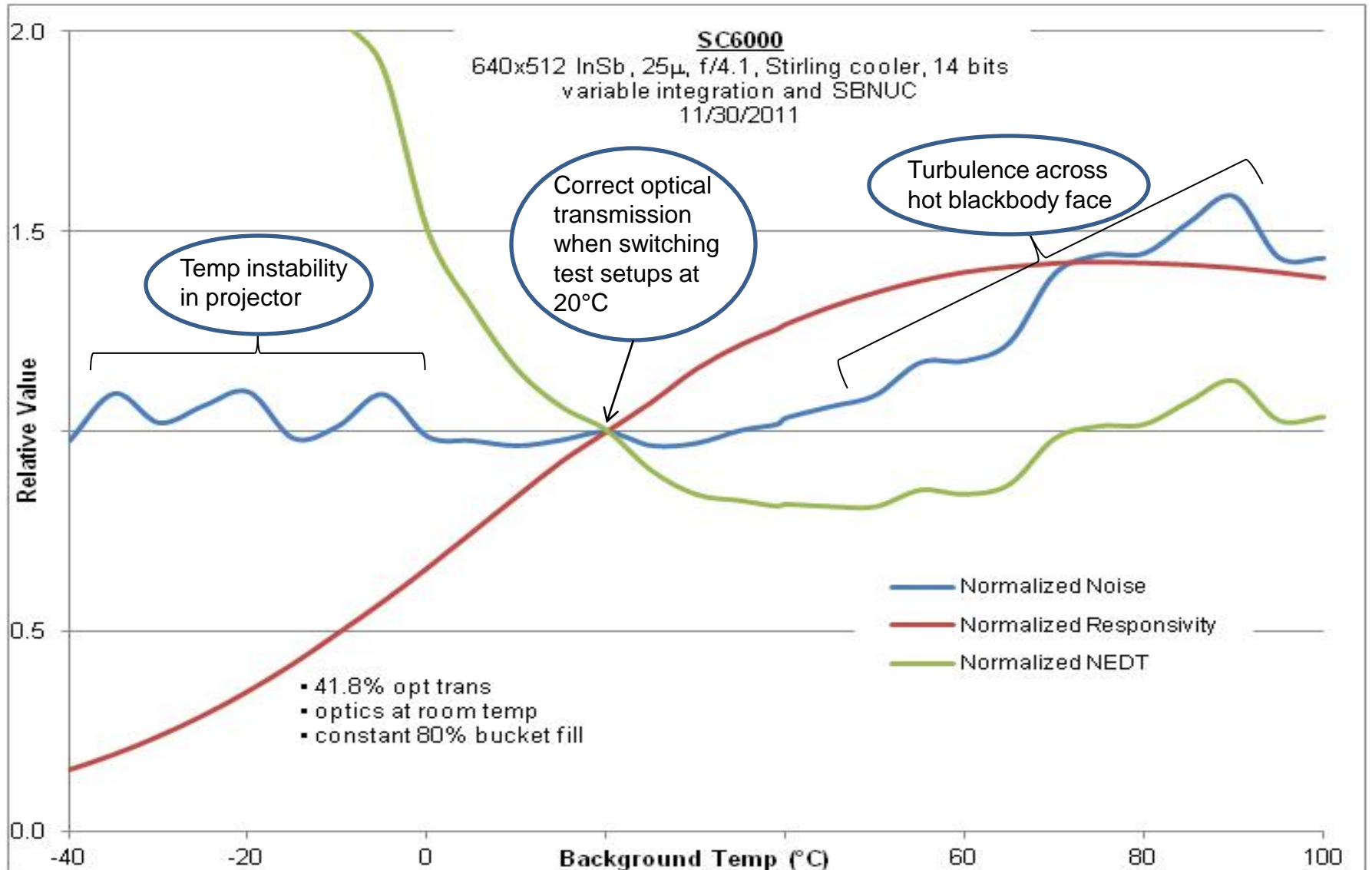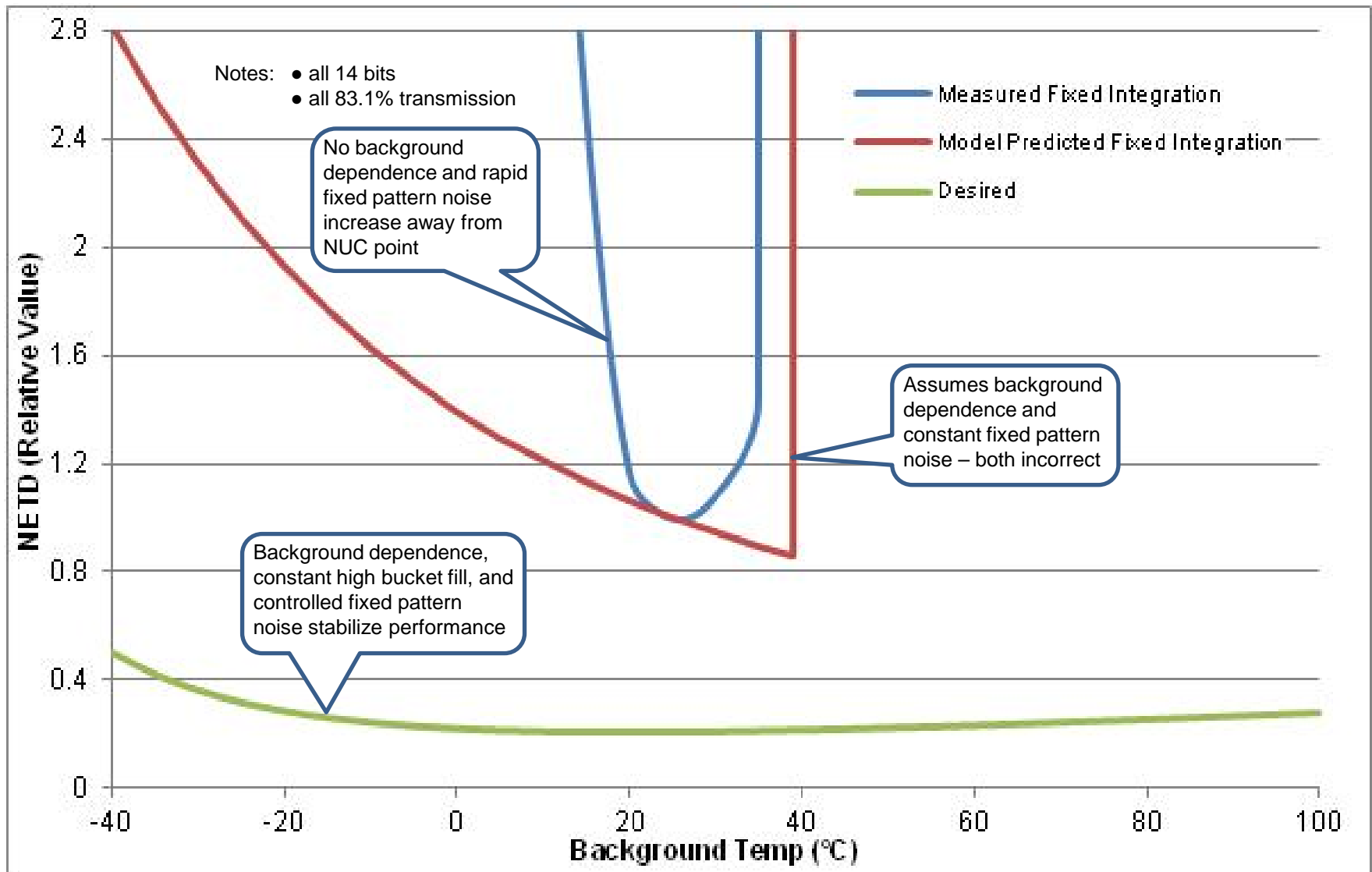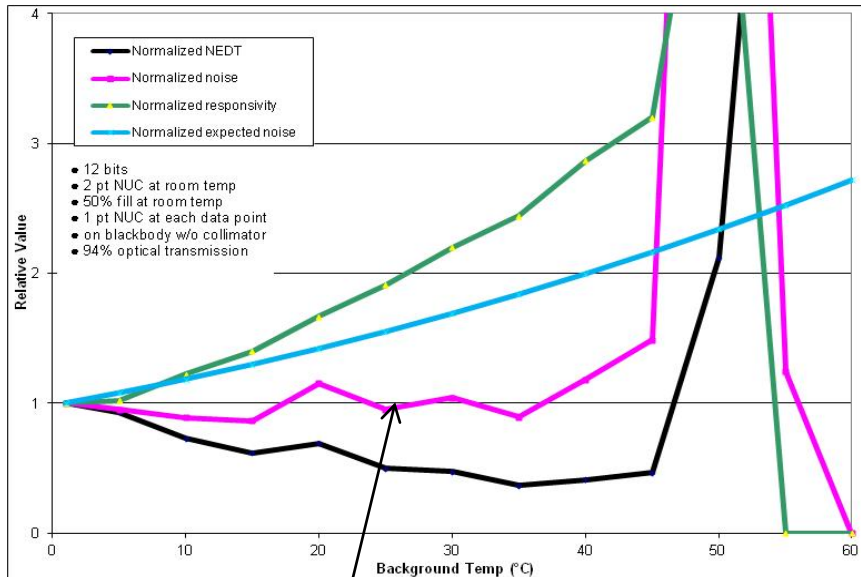
- 12 bit digitization depth prevents identification of smaller noise sources -- i.e., sensor is quantization limited as indicated by flat noise performance
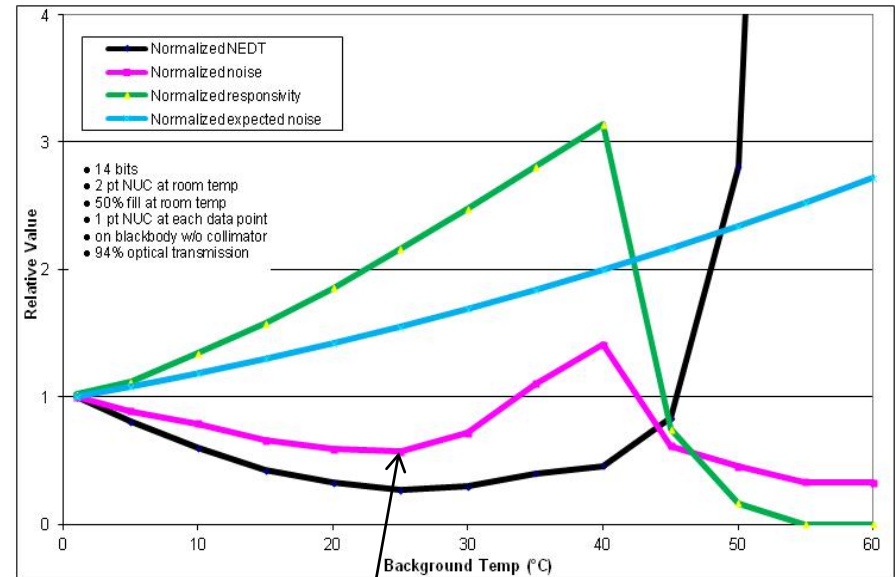
- Deeper 14 bit digitization depth allows identification of smaller noise sources -- in this case the tell-tale sign of gain based fixed pattern noise

Model Lessons

- **Improved model would agree with measurements**

  - Quantization noise is impactful at ≤14 bits

  - Sensors are not background limited

  - Fixed pattern noise is far from constant

Test Equipment Issues

- **Appropriate low background test equipment does not exist**

  - Use of scene projector is labor intensive and not cost effective

  - Scene projector is not really portable

  - Scene projector was not designed for radiometric accuracy needed for

    imaging sensor work

  - Scene projector lacks uniformity and operability for high resolution work

  - Scene projector is thermally slow compared to blackbody

  - Scene projector has limited background operating range

Observations

- Flight crew complaints were verified

  - Lack of test equipment prevented earlier discovery

  - Pervasive issue

- A scene projector is a terrible thing to waste

  - Overly complex for what should be a simple task

  - Lots of shortcomings which required workarounds

- The performance model is good but the hardware doesn't agree with it

  - Complex model

  - Complex hardware

  - Fix one or the other or both

Recommended Path Forward

- Spec systems from -40°C to ≥100°C

  - Currently room temp only

- Fix sensor design to agree with performance model

  - Underway at Edwards beginning in 2008

  - Prototype imaging at Edwards since 4 Jan 2012

  - Future upgrades planned

- Require test data over that range

  - From -40°C to +100°C

- Develop capable affordable test equipment to get that data

  - In lieu of $1.5M scene projector

  - Using standard lab data collection techniques

  - Underway at Edwards with 2012 SBIR

Scene Projector Replacement

Where we are

fast, dynamic scene projection of low quality imagery and backgrounds

>$1M, >1000 lbs, >5kW poor radiometric accuracy and thermally slow

Where we're going

Static projection of high quality backgrounds and simple targets

<$0.15M, <150 lbs, <1.0kW high radiometric accuracy and thermally fast
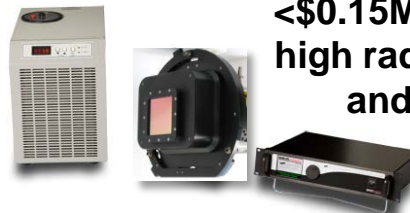
Blackbody in a dewar

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Abstract

Following an in-flight squawk for poor and unstable image quality during pre-deployment operational testing at Edwards, the Benefield Anechoic Facility (BAF) electro-optics laboratory set about to duplicate what was suspected as a background temperature related sensitivity issue with the relevant family of sensors, specifically midwave staring FLIRs. The specific system in question was designed in 1992 and fielded in 1994 having relied on existing performance models available at the time which indicated the performance should have changed only slowly and tolerably as background temperature varied. However, experience at Edwards showed considerable sensor change in sensitivity related to background flux even over the seemingly small 20°C temperature variation at Edwards from late afternoon when the flights would originate and later in the evening when data acquisition was undertaken. Note that real operational environments can involve backgrounds from -40°C in northern latitudes to well over +40°C in tropical and desert areas. These were the limits used for this particular system and in fact are still in use today due to design limitations which prevent operation above +40°C. A reasonable specification for sensors of this type to make them operationally suitable would be from -40°C to +100°C to accommodate hot environments populated with operating vehicles. Note also that such backgrounds can even occur within a few frames of video as sensors observe a cold sky and then a hot desert. Multiple scenarios can stress sensors between these limits. Issues related to duplicating and quantifying sensor performance under these conditions were:

- No piece of commercial test equipment existed that is specifically designed to make sensitivity measurements on tactical sensors at other than room temperature. These measurements are known as noise equivalent temperature difference (NETD) and represent that temperature difference on a large resolvable target at which the sensor signal to noise ratio is 1. These measurements are repeatable and accurate at room temperature although test equipment temperature difference measurement accuracy in the ballpark of 5mK (5 thousandths of one degree centigrade or Kelvin) or less is needed and is generally provided by available equipment at room temperature. The

issue is making such a measurement at low background where frosting of the target occurs.

- As a result of test equipment limitations and rosy model predictions, such measurements have never been made, with designers relying instead on the industry standard performance model to predict performance above and below room temperature. Subsequent lab data on multiple sensors at Edwards showed this reliance to be unsubstantiated. Cited references describe the actual data, their implications, a pathway to solution, and finally progress to date. That discussion is outside the classification of this paper and will not be repeated here. This paper covers the issues and needed solutions related to getting accurate test data on these sensors. As of this writing, the Edwards BAF EO lab is the only facility in the country to have made these measurements.

To attempt to replicate flight conditions, it was suspected that the Edwards Large Format Resistor Array (LFRA) might be able to generate low temperature backgrounds and make sensitivity measurements given its specified capability to operate from room temperature at +20°C down to low backgrounds at -40°C since the resistor array itself is enclosed in a vacuum dewar, which prevents frosting when operated below freezing. And the specific performance issue related to the flight system in question and all others in the field today is performance fall-off below room temperature. This suspicion proved to be correct with the following caveats:

- The LFRA uses an 8 pound image plane heat sink for stability and uniformity. Such high thermal mass slows down changes in background such that a move of 5°C requires 30 minutes. Therefore, making what turned out to be a 13 point data run from +20°C to -40°C required 8 hours, or about 10 times longer than such measurements would normally take on a blackbody.

- The LFRA has a temperature accuracy of ±0.3°C, which is inconsequential for projecting dynamic imagery, but is high when making NETD measurements. This error was uncorrectable and made part of the data. It was deemed to be tolerable given the large 60°C background range we were testing over and further minimized by using relatively large 5°C temperature spread over which to calculate responsivity.

- The LFRA has low optical transmission in spite of its advertised 90% per window (2 of them or 81% advertised overall) performance. Lab measurements indicated a real value of about 35%, which pushed the optical transmission of the complete lab setup down to a measured value of 30.0% after the 91% collimator and 94% sensor optics were included. Once quantified, this value could be corrected in the data. And it was tolerable given the large variation in sensor performance which was still measurable. Higher transmission would have made performance variations more evident, however.

- The LFRA is not radiometrically calibrated meaning that a commanded input is unrelated to either the absolute or relative temperature of the projected imagery. This required considerable blackbody correlation and projector command adjustment to achieve our desired target differential temperature of 5°C above the background. Such a relatively high target contrast also helped mask the LFRA's ±0.3°C background accuracy. Once established, however, the target contrast remained constant over the complete background range.

- The complexity and $1.5M price tag of LFRA are appropriate for its intended purpose of projecting dynamic low quality missile warning imagery with embedded hot spots up to 600K, but are inappropriate for making repeated mundane NETD measurements with a simple uniform 1K static image typically done with a $20k blackbody at room temperature. Having said that, the LFRA proved amazingly reliable and has never failed after months of repeated cycling over its entire temperature range and beyond.

- The LFRA is power hungry and requires 5kW of 3 phase power just for the cooling system. Such high power requires special wiring in the lab, and detracts from its ability to be moved.

- The LFRA has poor uniformity and operability with about 3% of the 1024^2 pixels being more or less inoperative. This limitation was made tolerable by using two large 1320 pixel areas in which to average both the target and background fluxes. Therefore, pixel outages and non-uniformities were averaged out. This is typical for NETD measurements but would disqualify LFRA from making high resolution measurements.

- The LFRA has a limited temperature operating range of +20°C to -40°C owing to the temperature sensitivity of the in-dewar electronics and because of the volatility of the high performance coolant. This limitation means a separate blackbody test setup had to be used for temperatures above room temp up to +100°C. Some data manipulation was required to generate continuous data given the 30.0% transmission of the scene projector compared to the 59.9% transmission of the blackbody setup.

We were able to work around all the above limitations to make use of the only semi-appropriate piece of test equipment available to us, the LFRA. It proved invaluable in obtaining the first data of this kind ever taken, and it will continue to support evolution of improved sensors beginning in early 2012.

However, for future sensor development and testing at industry and government facilities, the following test equipment requirements are evident from the above discussion:

- The device must be uniform and unpixelated, i.e., a blackbody.

- The device must be radiometrically accurate to 2-3mK in both absolute and differential terms.
- The power must be standard lab at 120V, single phase, 20 amp.
- The device must be able to make high resolution measurements over background in addition to NETD.
- The device must be fast with temperature change capability on the order of 2°C per minute.
- The device must be simple, reliable, and hence affordable with a price tag no greater than 10% of LFRA with a goal of $100k.
- The device must operate over the entire specified background temperature range for sensors of this type or from -40°C up to +100°C.

This paper describes the actual testing methodologies and also describes progress toward development of a more appropriate test device and methodology to support retrofit of existing sensors and development of future ones.

1. INTRODUCTION:

This is the first paper describing the specific test methodologies and setups needed to acquire this test data in a manner that would answer the salient flight squawk:

"The FLIR looked pretty good when I took off and a while later it didn't."

After observing recorded flight imagery in late 2005, speculation was that the sensor was experiencing background related sensitivity issues to a much greater extent than the prevailing performance model would indicate. Replicating that situation in the lab and quantifying it were the challenges at hand.

Since no blackbody exists that can operate for long periods below freezing, the decision was made to program the scene projector to project a representative NETD target. A block diagram of the setup in the lab is shown in Figure 1.

The uniform background target was projected by the Santa Barbara Infrared 1024^2 resistor array run over its maximum recommended temperature range of +20°C to -40°C to simulate the low background portion of the anticipated flight regime of +100°C to -40°C. The image was projected through a 4" aperture f/3.6 midwave refractive collimator to one of the multiple InSb cameras used over the intervening 5 years of data gathering and design experimentation. The collimator has a 14.4" focal length and a 4" aperture, which will project a field of view of 7.69° using the 1024^2 resistor array. The FOVs of the cameras used for this testing were all less than 7.32°, resulting in uniform background throughout the sensor FOV. Thermographic data for bucket fill, noise and responsivity for the cameras were captured digitally using FLIR Systems' RTools® software package or with similar custom software as appropriate.
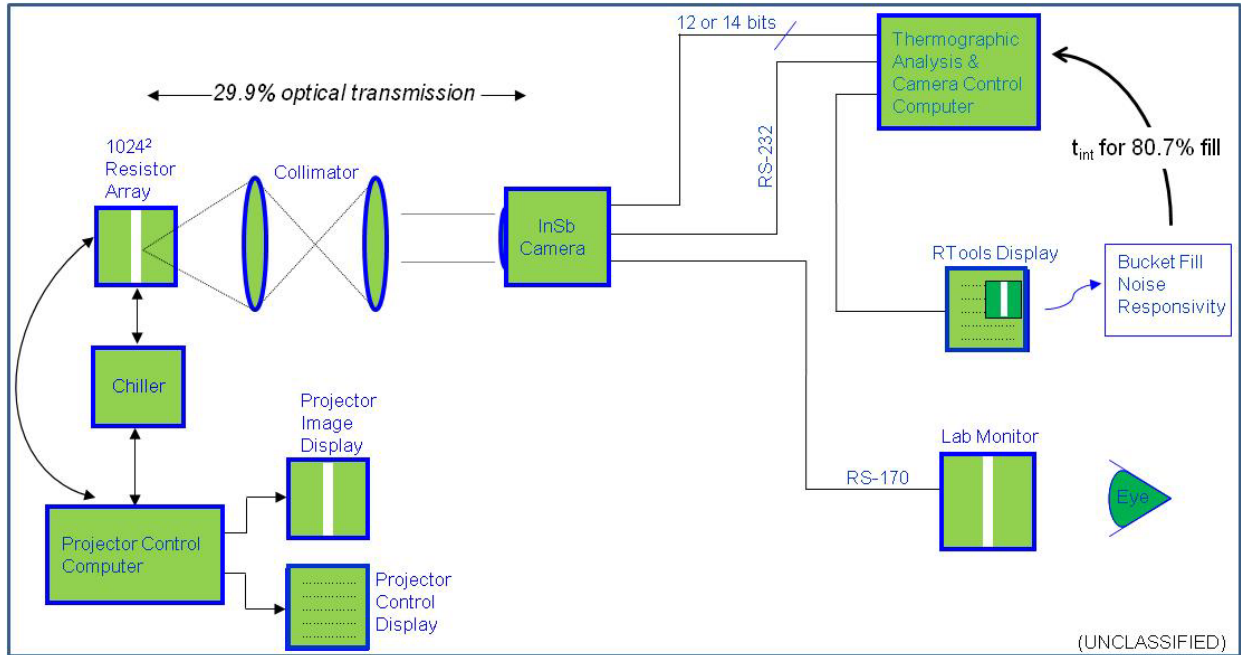
Figure 1. (U) Scene projector test setup used for low background NETD measurements.

Figure 2 shows a typical projected image as seen by one of the cameras. This vertical bar target was generated by a special command set programmed by Santa Barbara Infrared to drive the center 100 columns of the 1024^2 resistor array to produce the relatively large bar target shown. After some experimentation and correlation with a room temperature blackbody, the temperature difference of the lower portion of the bar was determined to be 5°C above the background. Given the highly conductive nature of heat exchange between the pixels and the substrate for this projector (i.e., negligible radiation loss), the bar would stay at that temperature difference as the substrate temperature was varied. This feature allowed a constant 5°C target to be used at all backgrounds between +20°C and -40°C. No other piece of test equipment on the market will do this.
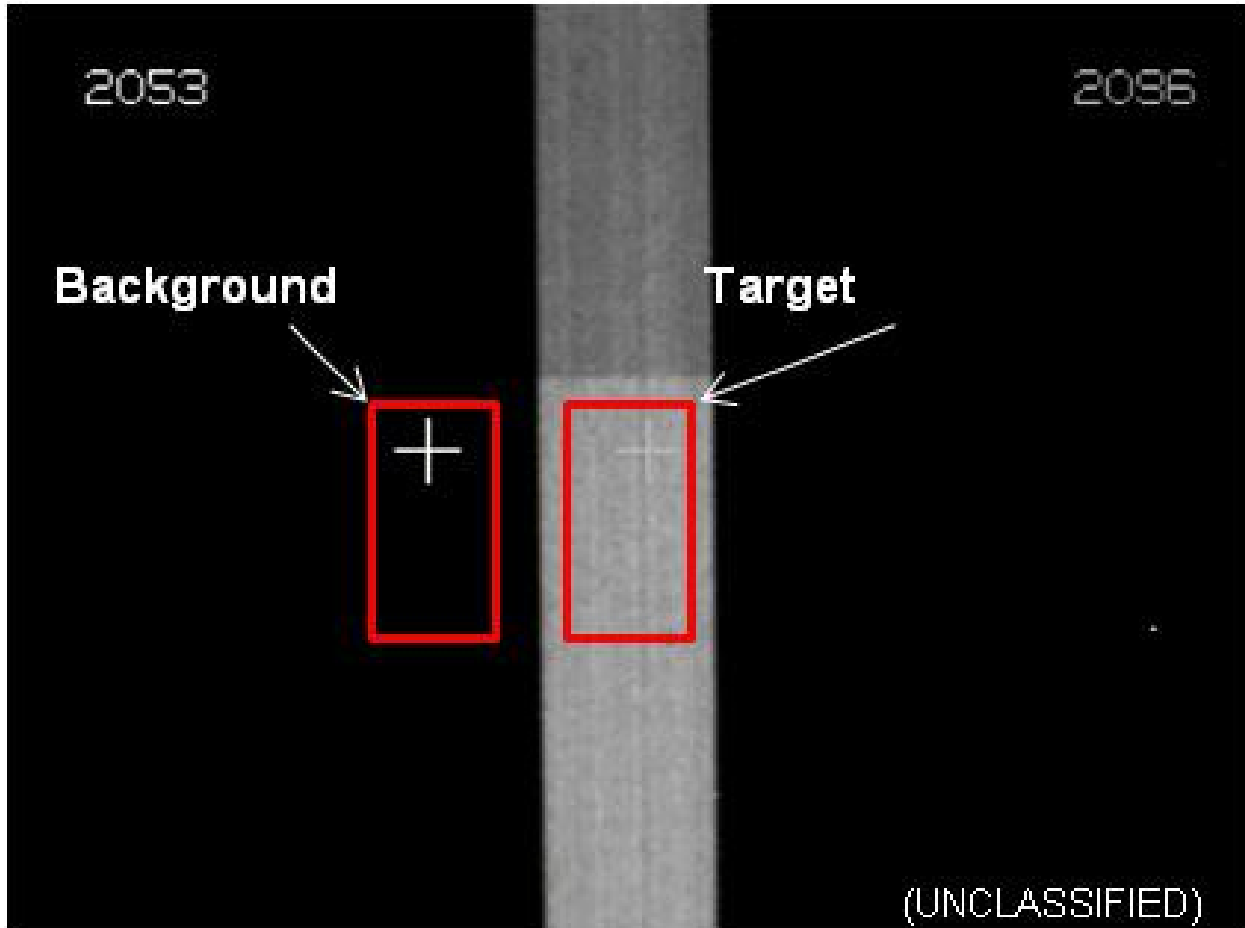
Figure 2. Typical 100 column 5° constant ΔT scene projector image at 20°C background.

Background noise combined with electronic noise, fixed pattern noise (FPN) and quantization noise is the standard deviation of the bucket fills for the pixels inside the left 1320 pixel region of interest as calculated by RTools®. Ten such readings were averaged at each temperature to improve accuracy. Responsivity is defined, for this experiment, as change in bucket fill in digital counts per degree C. It is determined by the difference in bucket fill between the two 1320 pixel sampled areas, one on the background and one on the 100 column 5° constant ΔT target bar, divided by the temperature difference. The background reading was also used to define bucket fill at the set temperature and subsequently to control integration time to keep bucket fill constant at 80.0% over background. NETD as defined herein is the noise measurement in units of digital counts divided by the responsivity in units of counts per degree C. The noise, responsivity, dynamic range, and NETD performance curves of the test FLIRs were plotted in absolute terms and also normalized to performance at appropriate points. The absolute and normalized values were then used to extrapolate performance up to 500°C background using curve fit coefficients from the measured data.

For blackbody measurements above +20°C, the setup was similar to that shown in Figure 1 except the collimator and scene projector were replaced with a blackbody. Cameras used were then focused on the blackbody at their minimum focus distance of

about 6 feet. Note that the difference in optical transmission between the 30.0% on the scene projector and the 59.9% on the blackbody produced a requirement to correct the blackbody data to an equivalent 30.0% transmission to generate a smooth performance curve from -40°C to +100°C.

TEST OBJECTIVE:

Our goal from the beginning of this work in late 2005 to first publication of findings in 2008 was to accurately relate our lab findings to the pilots' squawks so we could explain the relevant phenomena and thereby plan effective redesign actions. As data accumulated, it became apparent that the pilots' squawks were real and that six specific design changes were needed to correct them. Those changes and their impacts have been detailed in previous referenced publications and will not be repeated here. Suffice it to say that as of October 2011, all those changes have been incorporated into a prototype sensor, which is operating as predicted. This paper details the trials and tribulations involved in that effort. Those trials and tribulations are themselves significant and will result in new test equipment and methods.

TESTS PERFORMED

Tests performed were:
1) Camera responsivity and noise vs integration time at backgrounds of +100°C to -40°C using scene projector, blackbody and collimator for the prototype sensor operating with fully automatic integration, fixed integration with manual level correction simulating a perfect scene based NUC, and fixed integration without scene based NUC
   - Develops table of noise values at each background and integration time for each of the three operating modes
   - Develops table of responsivity values at each background and integration time for each of the three operating modes
   - Allows curve fit and noise parameter generation to extrapolate data to other optical transmissions, f-numbers, and backgrounds

4. RESULTS & ISSUES:

Figure 3 shows a typical performance curve resulting from this process along with notes depicting modeling inconsistencies specifically related to noise sources. These inconsistencies required many data corroboration re-runs, which consumed many days of lab time given the slow thermal response of the scene projector back plane.
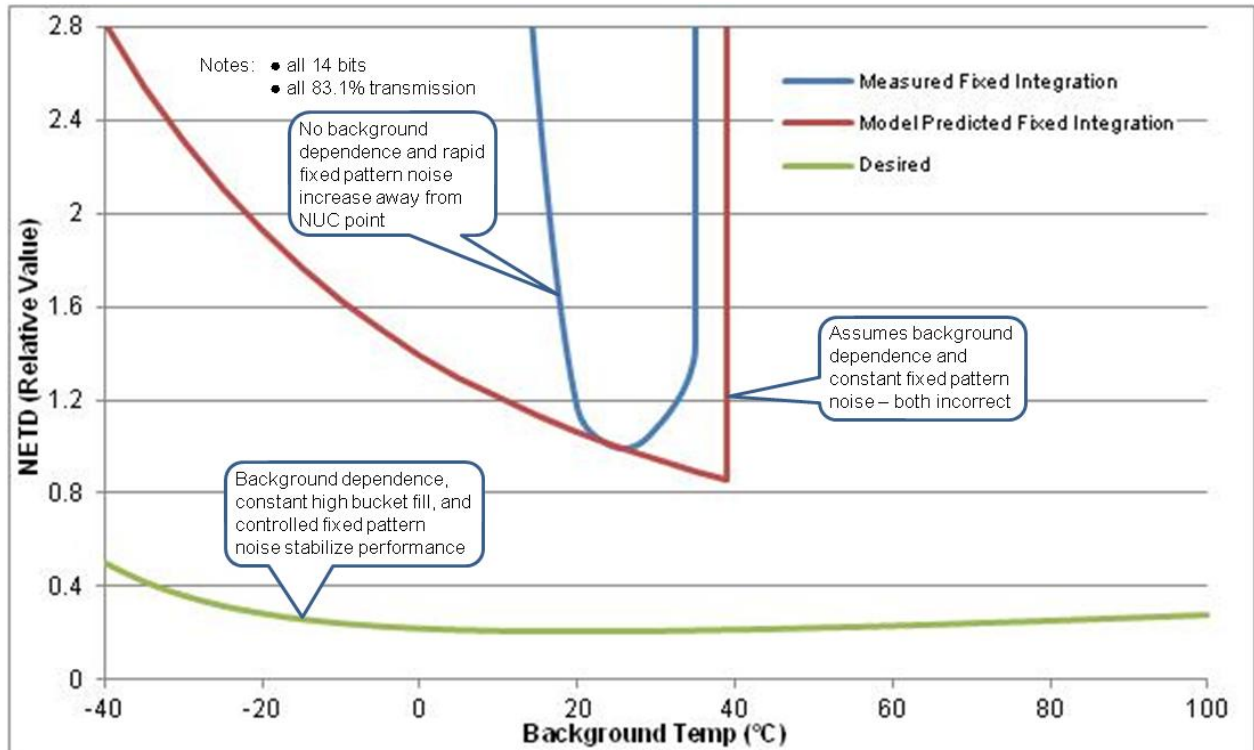
Figure 3. Typical NETD performance measurements and extrapolations over a background range of -40°C to +100°C.

To relate our data to operational systems of the present and future, several issues had to be overcome:

A. Low Optical Transmission on Scene Projector:
The low 29.9% optical transmission of the scene projector setup needed to be extrapolated to a value representative of operational designs, which are typically in the 70-90 percent range. Increasing optical transmission not only makes the data more relevant, but also resulted in non-linearly increasing the effect of fixed pattern noise caused by bucket fill variation with background. These bucket fill changes caused rapid increases in level based fixed pattern noise, which comprises 80% of all fixed pattern noise. This discussion has been covered in previous referenced publications. Figure 4(a) shows the curve fit process that allowed total noise to be quantified relative to bucket fill to allow it to be related to higher optical transmissions and hence lower bucket fills at low background. The resulting noise equation provides good fit to the measured data, especially at lower background and hence lower bucket fill associated with higher optical transmissions. Figure 4(b) shows noise values for two representative optical transmissions of 83.1% and 87%, indicating that the higher transmission allows deeper bucket fill depletion as background is reduced resulting in higher noise. Next, Figure 4(c) shows the noise extrapolations used for NETD predictions, which indicate that higher transmission with its more rapid bucket fill starvation at low background actually results in higher noise to essentially nullify the benefit of the higher transmission. It should also be noted that previous published work determined that the optimum optical transmission for this class of sensor is approximately 83.1%, which

allows integration time to increase to 16.6msec at -40°C. Figure 4(d) shows the extrapolated measured performance compared to that of a more operationally desirable design. The details of that design have been published elsewhere (ref 5) and will not be repeated here.
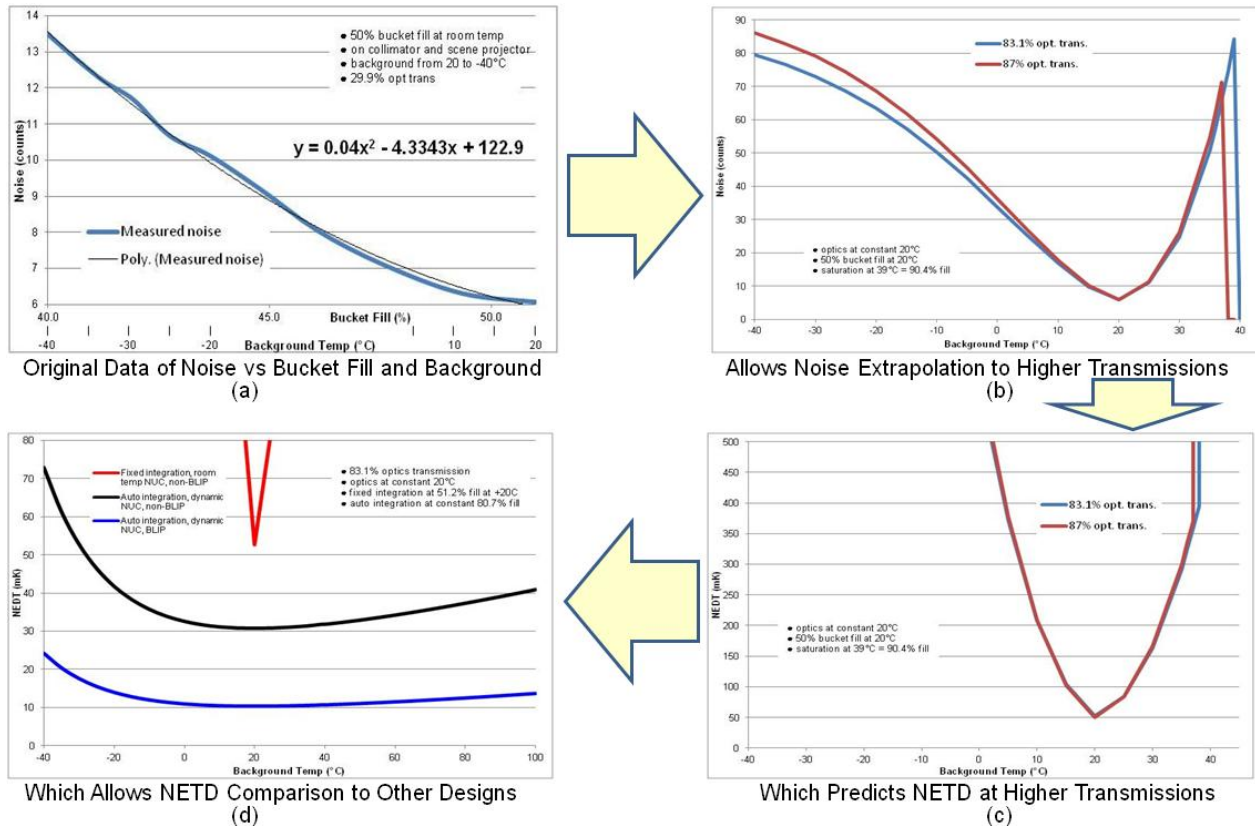

Figure 4. Curve fitting process allows generation of relevant data and comparison to alternative designs.

B. Background and Fixed Pattern Noise Behavior:

The original data could not be correlated with the existing culturally accepted performance expectations for these sensors, namely that they should exhibit some background dependence and that fixed pattern noise is constant once corrected at room temperature. Figure 5 shows those assumptions to be unsupported by measured data. As can be seen:

- Responsivity behaves as expected and declines consistent with dW/dT. Note that this effect, if normalized to room temperature as shown, is independent of optical transmission.

- Noise, however, is not independent of optical transmission and behaves in a completely different manner than is conventionally accepted. Measured data from all sensors show this same characteristic where total noise, consisting of quantization, background, fixed pattern, and electronic, departs from an expected slope within 2-3°C from the NUC point. Note that this departure is dependent on optical transmission with the data shown taken at 29.9% on the scene projector.

Higher optical transmission results in more rapid bucket fill swings with background and hence more rapid increases of fixed pattern noise away from the NUC point, which in this case is at 20°C. Lab data showed that the straightforward relationship between optics transmission, bucket fill and background can be expressed as shown in equation (1).

(1)   **bucket fill $\propto$ (bkround at temp T)*(opt. trans.)+(bkround at optics temp)*(1-opt. trans.)**

Once a baseline bucket fill is determined for a given design and background, this relationship can then be used to predict bucket fills for different f/#'s, optics temperatures, or other design parameters.

This strong effect of bucket fill on FPN is contrary to the existing standard performance model, which assumes FPN is constant over background once corrected, which is typically done at room temperature. All lab data indicate this is not the case with FPN increasing sharply as the background is moved away from the NUC point by as little as 2-3°C, representing about a 1% change in bucket fill for 83% transmission at room temperature for example. Equation (2) was empirically determined from lab data (Figure 4(a)) to relate bucket fill to total noise, which for this class of sensor is all FPN.

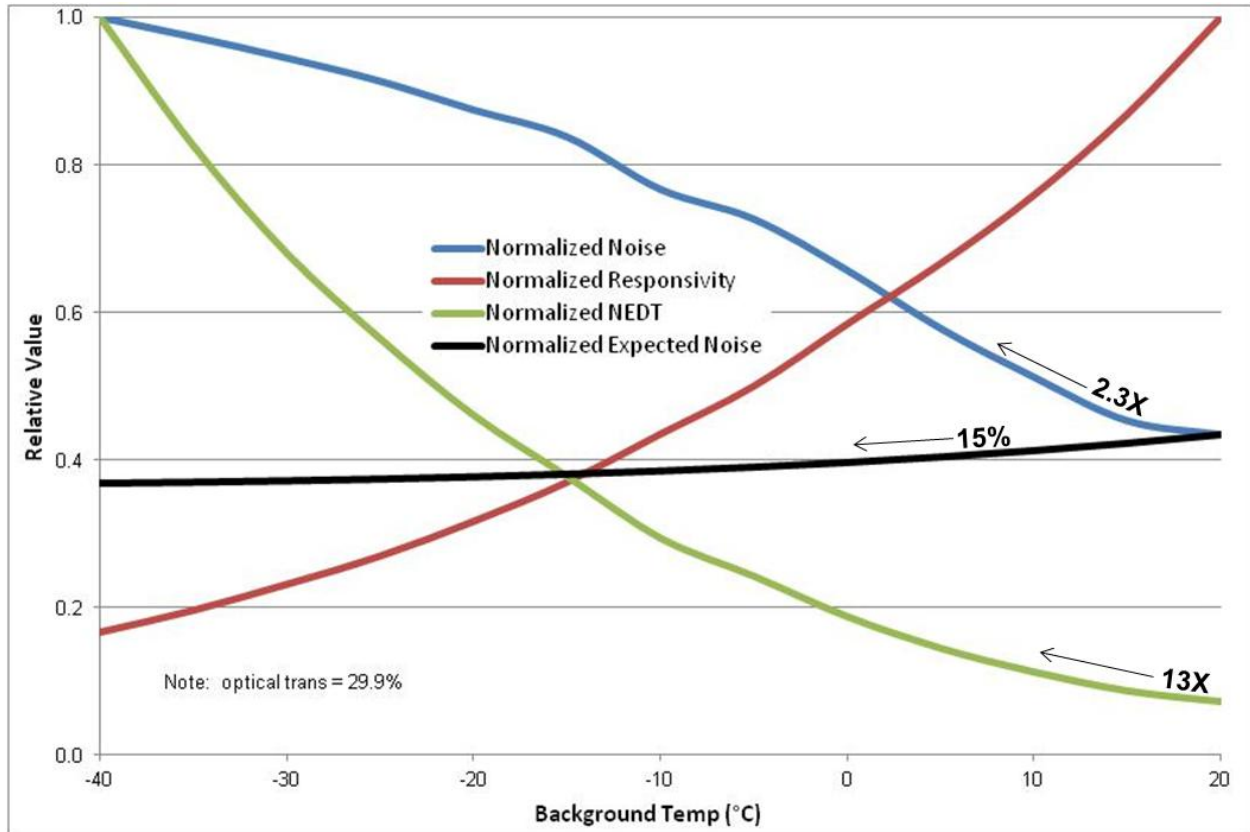(2)   **total noise = 0.04*(bucket fill)^2 – 4.3343*(bucket fill) + 122.9**

Figure 5. **Measured data does not agree with expected sensor background and fixed pattern noise performance.**

Many background runs over the full temperature capability of the scene projector were required to understand the relationship between the aforementioned four noise sources. The time span required to do this involved several days of data acquisition spread over several weeks with a single run requiring about 8 hours given the slow thermal response of the projector back plane. In the end for this class of sensor, it was determined that fixed pattern noise was the dominant component with 80% of FPN being level based and 20% being gain based. In addition, no evidence of background noise influence could be determined. This is contrary to the existing performance model where background noise, defined as the square root of the background, is assumed to contribute to total noise. No such contribution was ever seen. See the referenced publications at the end of this paper for detailed discussion of this issue and specific solutions to it.

C. Quantization Noise Behavior:
Over the course of the many weeks required to identify and quantify noise sources, it finally became apparent that quantization noise could not be ignored. Figure 6 shows representative noise performance for this class of sensor with a 12 bit compared to a 14 bit digitizer. Note that in both cases, level based fixed pattern noise has been removed via a single point level update at each data point to allow identification of lesser noises. Had this not been done, level based FPN would have swamped all other sources preventing their identification. Clearly, the flat noise performance of the 12 bit design

prevents identification of smaller noise sources such as gain based fixed pattern, electronic, or background. As can also be seen, no indication of background dependence is evident in either case. A much more complete discussion of these noise components is given in the references and will not be repeated here. For purposes of this discussion, test equipment capable of operating below freezing would have made these measurements more evident, especially in the 14 bit case. And as sensors evolve to 16 bit performance, availability of such devices will be critical so background and electronic noise components can be quantified.
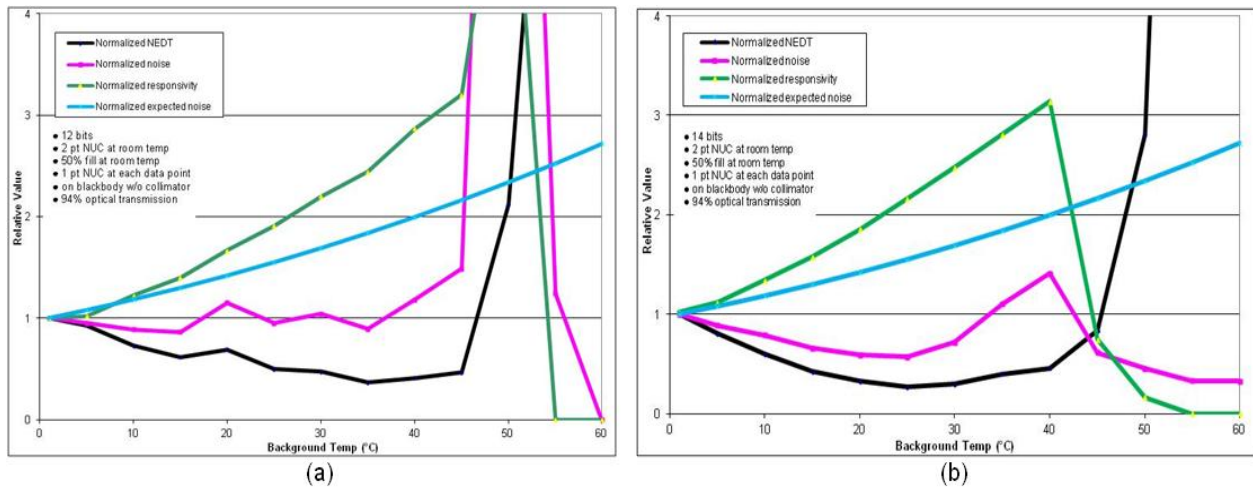
Figure 6. Shapes of noise curves is clear indication of quantization noise (a) and of gain based fixed pattern noise (b).

D. Data Correlation Between Test Setups:

Given the inability of the scene projector to be operated above 20°C, a separate blackbody setup is required to collect data between 20°C and +100°C. To do that, we make measurements on both test setups and then correct the blackbody measurements for the transmission of the projector or vice versa. Both setups use the same sensor optics and collimator. To be specific, the projector and blackbody setups have the measured characteristics shown in Table 1.

Table 1. Measured and inferred optical characteristics of the projector and blackbody test setups.

	Transmission
Projector Setup	~30.0%
Blackbody Setup	~59.9%

Note that the test setup only allows a transmission-emissivity product measurement of the complete path. Once the transmission of the blackbody setup is established with its assumed 1.0 emissivity, then a simple curve match to the projector data can be made once the measured 30% transmission-emissivity product of the projector is established. It can be seen that the transmission of the projector resistor array is quite low at 30%, which will vary slightly on a setup to setup basis. This value is consistent with other measurements made and published over the last several years.
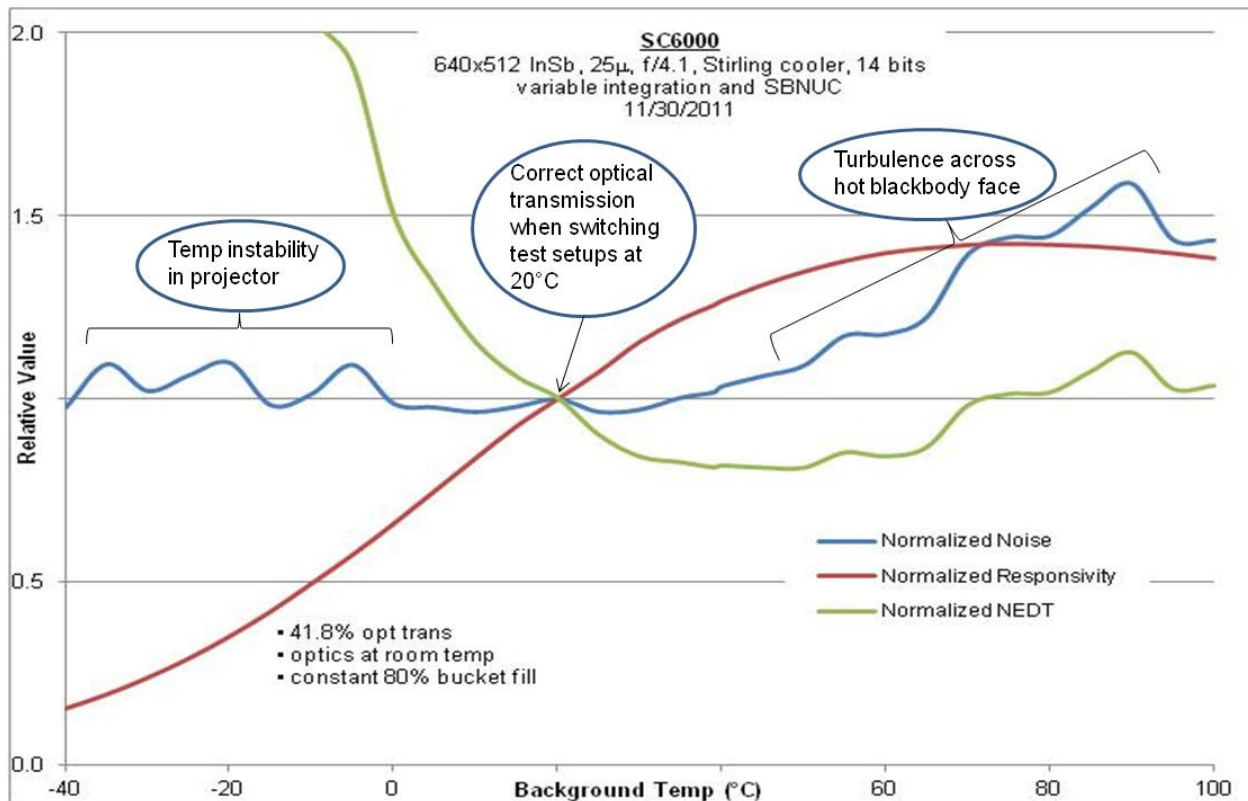
Figure 7. Process of adjusting data between two test setups with different transmissions and emissivities.

5. SOLUTIONS:

Solutions to the issues presented in the preceding paragraphs are discussed in the following section. Given the extensive data taken over the last 5+ years, it is clear that both the performance models and the hardware need to improve.

A. Model Issues:

1. Model should account for quantization noise: Data indicate systems at or below 14 bits of digitization are quantization noise limited. This is particularly true for 12 bit designs running fixed integration time, which restricts bucket fill to no greater than 50% at room temperature to prevent saturation on typical tactical backgrounds up to about +40°C. This limitation prevents these systems from compensating for electronic and background noises and absolutely precludes their achievement of background limited noise performance. The performance models should reflect this.

2. Model should account for non-constant fixed pattern noise: Data indicate non-linear influence of bucket fill changes on both level based and gain based fixed pattern noise with a measured 80/20 split, respectively. Noise performance of the various sensors tested is consistent and shows a rapid noise increase for bucket fill variations of about 1% or less up or down. These data do not support accepted modeling dictum which says fixed pattern noise is low and constant once corrected at room temperature. Quite the contrary, both gain and level based fixed pattern

noises vary non-linearly with changing bucket fill. The performance models should reflect this.

3. Model should account for non-background limited noise performance: None of the sensors tested exhibit influence of background on their total noise measurements. Although limited data is available for constant bucket fill designs, it can be said that fixed integration designs with 14 bit digitizers using 50% bucket fill at room temperature are not background limited. The performance penalties associated with this characteristic have been documented in the referenced publications. Additional data from the Edwards constant bucket fill design will be available in early 2012. That design is expected to be the first sensor to come close to background limited noise performance over tactically suitable backgrounds.

A. Test Equipment Issues:

1. Use of scene projector is labor intensive and not cost effective: The scene projector was designed to produce dynamic images at relatively stable and inconsequential background temperature. It is, however, the only piece of test equipment available today that can project a static image for different backgrounds with a slow rate of change. Once changed, the background temperature of the emitter array has been demonstrated to be stable within ± 0.3°C, which is acceptable using the workaround implemented for the testing described herein. The slow rate of change of the array increases cost of testing by an order of magnitude at least compared to conventional blackbody response times. Specifically, taking data from room temperature to the lower limit of the device at -40°C requires 30 minutes for each of the 13 data points resulting in a full 8 hour day for two people. A blackbody type device could perform this run in less than an hour with better accuracy.

2. Scene projector is not really portable: Given the over half ton weight of the device and its unique three phase and single phase 220V power requirements, the scene projector is difficult to relocate on short notice. Our testing requirements would be better served by a device using standard single phase 120 volt power and weighing somewhere in the 150 pound range.

3. Scene projector was not designed for radiometric accuracy: The stated purpose of the scene projector is to produce rapidly changing low resolution, low quality imagery at fixed slowly changeable background for consumption by non-imaging missile seekers. As such, the only radiometric parameters required or specified were max emitter temperature of somewhere in the 600K+ range and an array substrate range of +20°C to -40°C. The observed ±300mK tolerance on the substrate temp is consistent with the intended application of the device for missile seekers against inconsequential backgrounds. For our purposes, such a loose tolerance is not inconsequential but was able to be worked around by using large 10°C temperature spreads from which to make calculations. This diminished the effect of the variance although a device with blackbody accuracy in the 3mK range would negate workarounds and improve accuracy.

4. Scene projector lacks uniformity and operability for high resolution work: The low quality imagery mentioned above refers to the uniformity and operability of the resistor array, which is about 97% operable and highly non-uniform.   Note that although a non-uniformity correction lookup table is part of the device, the input parameters cannot be better than the imaging sensor used to measure them.   The end result is that the imaging sensor under test will be able to see residual non-uniformities (see Figure 2).   Worse yet, the non-uniformities are not constant and require periodic updates as the array ages.   This is unacceptable for high quality image projection, but was able to be worked around by averaging large areas of the array and avoiding making high contrast or high resolution measurements.   For imaging midwave sensors, high quality imagery with 100% operability and uniformity below the threshold noise of the sensor under test is required.   Many failed experiments have shown that these uniformity and operability requirements can only be achieved by a non-pixelated blackbody type device

5. Scene projector is thermally slow compared to blackbody: The scene projector changes its substrate temperature by about 5°C per 30 minutes.   Once stable after this time, data can be acquired.   That meant for a 13 data point data set, an entire 8 hour shift for two people was required.   A blackbody will be at least an order of magnitude faster.   Given the lack of an alternative device, the slow response time of the scene projector was accommodated.

6. Scene projector has limited background operating range: As previously stated, the background range of the scene projector is limited to +20°C to -40°C.   This restriction precludes exploration of high background conditions typical of desert environments or high radiation environments such as those populated with operating vehicles, fires, certain industries, etc.   This restriction required the workaround of using a blackbody to fill in the range between +20°C and +100°C.   Applying this workaround required correction of responsivity for the optical transmissions of the respective test setups with the scene projector at 30.0% and the blackbody at 59.9% -- an inconvenient and time consuming process.   A wide background range blackbody would negate the need for such data manipulation to get smooth continuous curves.

7. Scene projector has low optical transmission: As mentioned above, the low 30.0% optical transmission of the scene projector strongly masks the effects of bucket fill changes caused by background variation. These bucket fill changes cause a non-linear fixed pattern noise increase for bucket fill changes of less than 1% representing only a 2-3°C change in background from room temperature. The low transmission masks this effect resulting in potentially lower data accuracy than would a transmission of 80% or so representative of operational systems. This issue could not be worked around and had to be tolerated.   A simple blackbody in a dewar can easily exceed the goal of 80% transmission.

6. PATH FORWARD:

The path forward is clearly to build an appropriate piece of test equipment based on the requirements implied above. Figure 8 shows a comparison of where we are today with the scene projector being the only option for making these kinds of measurements compared to where we are going in the future with a blackbody type device in a dewar to allow fast, accurate, uniform, low power, high transmission, portable measurements.
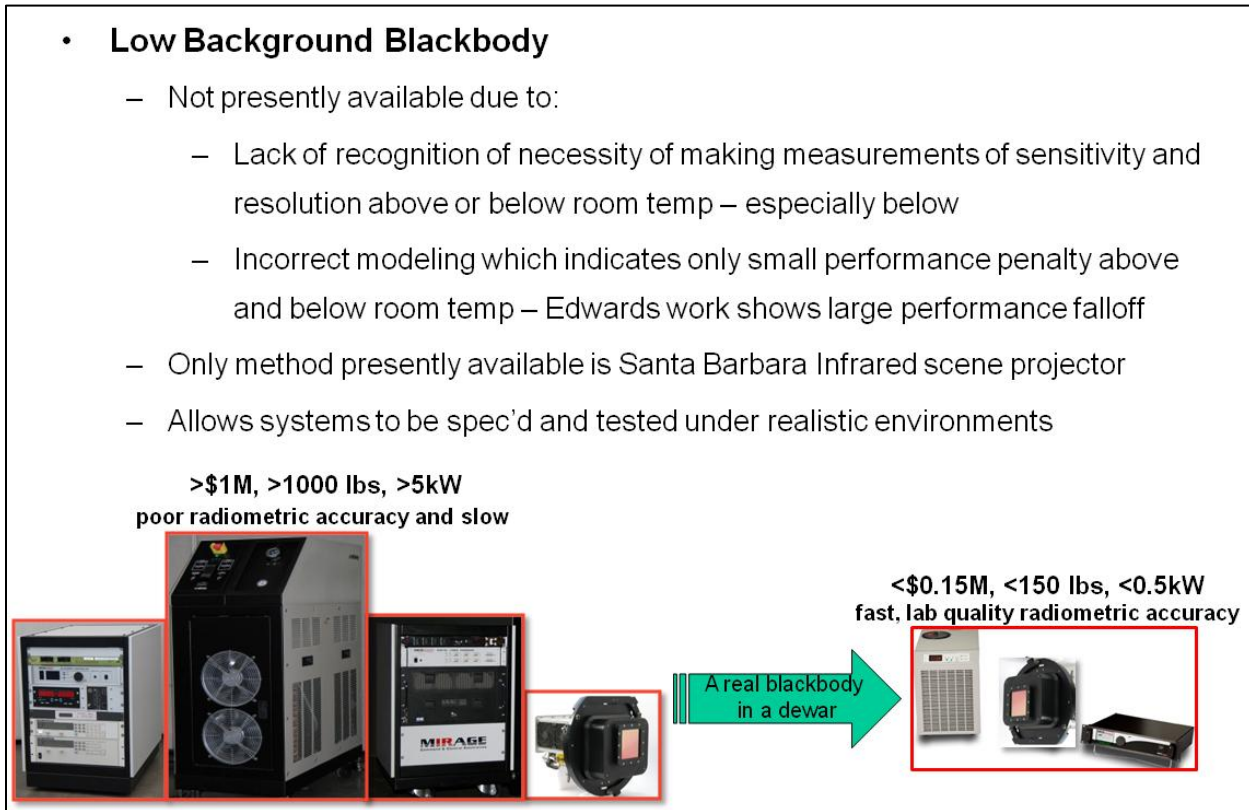

Figure 8. Path forward to achievement of acceptable wide background test equipment.

To achieve this end, Edwards launched a small business innovative research (SBIR) program in 2011 to begin the design and development of such a device. As a result of this program, a prototype device should be running in 2013.

(U) References:
1. H. Pham, F. Crawford, M. Mele, D. Hatfield, "Measured Contrast Performance of a Midwave Staring FLIR", MSS Passive Sensors, February 2008
2. H. Pham, F. Crawford, D. Hatfield, "Measured NEΔT Performance of a Midwave Staring FLIR", MSS Passive Sensors, February 2009
3. Mark A. Massie, Todd R. Cicchi, Eric J. Woodbury, Huy Pham, Dean Hatfield, Paul McCarley, "Optimizing and Automating FLIRs for Low Contrast, Low Noise Operation", MSS Passive Sensors, February 2010
4. H. Pham, D. Diebel, F. Crawford, R. Sendall, M. Massie, K. Louton, D. Hatfield, "Progress Toward a Background Limited Midwave Staring FLIR", MSS Passive Sensors, February 2011
5. H. Pham, Lt. Ryan Buatala, Dean Diebel, Mark Massie, Dean Hatfield, "First Near-BLIP Midwave Staring FLIR Over Background", MSS Passive Sensors, March 2012